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DC GENERATORS FOR UTILIZING WIND POWER

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16. Abstract

Theoretical considerations are explained and experimental findings pertaining to the possibility of utilizing wind power with electromechanical units comprising various types of direct current machines.

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DC GENERATORS FOR UTILIZING WIND POWER

A. Carrer**

Theoretical considerations will be explained and confirmatory experimental findings pertaining to the possibility of utilizing the wind power by means of electromechanical units comprising various types of direct current machines will be illustrated. /376*

1. - GENERALITIES AND PURPOSE OF THE MEMORANDUM

The utilization of the wind energy by the operation of electric generators encounters appreciable difficulties because of the considerable discontinuity in the flow of the available energy, which generally does not correspond to the output energy needed ***.

This problem can be solved, for instance, by utilizing a storage battery which makes it possible to modify the availability of the energy produced by the wind engine to make it suitable for its intended use or by feeding the energy itself into a direct-current or alternating-current, constant-voltage network capable of absorbing the energy as it is being generated, that is whatever power is produced by the generator driven by the wind. For both of the special cases, which now have been considered, it is evident that it is necessary to have electric generators which are able to produce electric energy at constant voltage although they are driven at speeds which vary within very wide limits, and at the same time they must be

* Numbers in the margin indicate pagination in the foreign text.
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*** For information on the discussion it is useful to consult pertinent articles published on: Reports of the Annual Convention of the A.E.I., 1948, XXII.

able to deliver all the energy they may receive from the wind engine.

The problem is thus somewhat complicated and will be resolved by steps. It may be maintained that the first step in solving the problem is to build a generator which produces a direct-current or alternating-current emf of a practically constant value when it is driven at a variable speed.

The goal can be reached in the field of direct-current with diagrams including the amplidyne and ordinary machines.

The purpose of this communication is to point out two solutions obtained with direct-current machines beginning with a diagram studied by engineer Cesare Ponza di San Martino and Paolo Santini. The Supreme Council for Public Works, which has already in the past been interested in the argument under the direction of its president, professor Marco Visentini, has given Instituto Elettrotecnico Nazionale Galileo Ferraris the task of investigating the question in more depth and has supplied the necessary means for meeting the necessary expenses. The author sends his cordial thanks to the boards and to the persons who have been remembered, to professor Giancarlo Vallauri, who assigned the work to him, and to engineer Giorgio Brach-Papa, who has cooperated in carrying out the calculations and the experiments.

2. - THEORETICAL STUDY OF THE PROPOSED DIAGRAM

The diagram proposed for obtaining a constant voltage from a direct-current generator regardless of its speed of rotation is shown in Figure 1. Two amplidynes MT_1 and MT_2 with one loop, of the type with four equidistant brushes, are connected to each other mechanically or mounted on the same shaft as indicated in Figure 1 or geared together. MT_1 is the exciter, and MT_2 is the main generator.

The exciter has the primary brushes 1 and 3 connected to a source of constant voltage V_1 supplied, for instance, by a storage battery, which serves for pilot voltage, while the secondary brushes 2 and 4 are connected to brushes 3 and 1, respectively, of the primary circuit of amplidyne MT_2, whose secondary brushes 2 and 4 supply the output voltage V_2, which should be constant as stated above *). We will assume that the positive direction of current I_1 of the primary circuit of amplidyne MT_1, current I in the secondary circuit of amplidyne MT_1 and the primary of amplidyne MT_2, and current I_2 in the secondary circuit of amplidyne MT_2 are as indicated in Figure 1. We will suppose that the direction of rotation of the machines seen from the collector side is clock-wise and that the direction of rotation of the armature winding is also clock-wise. Then if terminal 1 on amplidyne MT_1 is connected to the positive pole of the pilot voltage V_1, terminal 4 of the main generator will be the positive pole for voltage V_2. Finally, it is assumed that saturation phenomena in the magnetic circuit will be disregarded.

Now that this has been stated, we can examine the diagram by writing the equations which represent the operation.

Designating the angular velocity of the group by ω in radians per second and referring to the three circuits (the currents I_1, I, I_2 pass through) as having resistances R_1, R, and R_2, respectively, we deduce:

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* For the notations and the conventions used in this work see: A. Carrer: Metadinamo (The amplidyne). Lectures in the advanced course in electronics at Turin Institute of Technology, 2nd edition, academic year 1948-1949, Levrotto e Bella, Turin.

$$\begin{cases} V_1 = \omega K_{31} I + R_1 I_1 \\ \omega K_{24} I_1 = \omega K_{31}' I_2 + R I \\ V_2 = \omega K_{24}' I - R_2 I_2 \end{cases} \qquad (1)$$

where K_{31}, K_{24}, K_{24}' refer to constants because, as has already been stated, we disregard magnetic saturation phenomena. By arranging the system according to I_1, I and I_2, we obtain:

$$\begin{cases} R_1 I_1 + \omega K_{31} I = V_1 \\ \omega K_{24} I_1 - R I - \omega K_{31}' I_2 = 0 \\ \omega K_{24}' I - R_2 I_2 = V_2 . \end{cases} \qquad (2)$$

Other equations can not be written with the exception of the equation pertaining to the load fed from voltage V_2, but this is not of any particular interest for the problem under consideration.

An examination of system (2) shows that if voltages V_1 and V_2 are assumed to be given, the values for the currents I_1, I and I_2 will be determined unequivocally. But this is not the case we want to consider, since we assumed that voltage V_1 was given, while we wanted voltage V_2 to become constant.

The difficulty can be overcome as shown in the following. Instead of voltage V_2 we will consider the emf E_2, which is produced in the secondary circuit of the main generator. Analytically, this means that the third equation is replaced by the following:

$$\omega K_{24}' I = E_2 \qquad (3)$$

and we assume that the armature feedback K_{31}' of the main generator itself is completely compensated for by a compensating winding C_2.

The second equation will then be without the term containing I_2 since it is replaced by the term $(K_{31}'-C_2)I_2$, which will /377 be equal to zero because it is assumed that:

$$K_{31}' = C_2 . \tag{4}$$

System (2) is then replaced by:

$$\begin{cases} R_1 I_1 + \omega K_{31} I = V_1 \\ \omega K_{24} I_1 - R I = 0 \\ \omega K_{24}' I - E_2 = 0 \end{cases} \tag{5}$$

which gives the following values for I_1, I and E_2:

$$I_1 = \frac{R}{\omega^2 K_{31} K_{24} + R_1 R} V_1 \tag{6}$$

$$I = \frac{\omega K_{24}}{\omega^2 K_{31} K_{24} + R_1 R} V_1 \tag{7}$$

$$E_2 = \frac{\omega^2 K_{24} K_{24}'}{\omega^2 K_{31} K_{24} + R_1 R} V_1 . \tag{8}$$

Among these values the one which is of most interest is the one which gives E_2. It is seen immediately that if:

$$R_1 R = 0 \tag{9}$$

then we have:

$$E_2 = \frac{K_{24}'}{K_{31}} V_1 \tag{10}$$

or the value of the emf E_2 would be constant, independent of the value of ω and proportional to the constant pilot voltage V_1 with the proportionality factor K_{24}'/K_{31}, exactly as wanted. This can not be achieved, but we can approach the ideal condition expressed by (10) in such a way that the value of the product R_1R will be as small as possible compared to the value of the term containing ω^2, at least above an appropriate value for ω.

This can be obtained by equipping amplidyne MT_1 with primary amplifier windings A_1 and secondary amplifier windings A_2 with a sufficiently large number of windings. The term:

$$\omega^2 K_{31} K_{24} \tag{11}$$

will then be replaced by:

$$\omega^2 (K_{31} + A_2)(K_{24} + A_1). \tag{12}$$

But by doing this the value of the ratio:

$$\frac{E_2}{V_1} \tag{13}$$

is reduced with respect to the value given by (9), and it is therefore advisable also to increase the numerator of expression (8) by introducing a primary amplifier A_1' in the diagram of the main generator.

After all, we can conclude that the diagram which best meets the fixed requirement is the diagram shown in Figure 2, where the values of I_1, I and E_2 are given, not by expressions (6), (7) and (8), but by :

$$I_1 = \frac{R}{\omega^2 (K_{31} + A_2)(K_{24} + A_1) + R_1 R} V_1 \tag{14}$$

$$I = \frac{\omega (K_{24} + A_1)}{\omega^2 (K_{31} + A_2)(K_{24} + A_1) + R_1 R} V_1 \tag{15}$$

$$E_2 = \frac{\omega^2 (K_{24} + A_1)(K_{24}' + A_1')}{\omega^2 (K_{31} + A_2)(K_{24} + A_1) + R_1 R} V_1 . \tag{16}$$

We see immediately that for $\omega = 0$ we get:

$$(I_1)_{\omega=0} = \frac{V_1}{R_1} \; ; \; (I_2)_{\omega=0} = (E_2)_{\omega=0} = 0 \tag{17}$$

as was to be expected. When $\omega > 0$ and increasing, I_1 is always decreasing and approaches $I_1 = 0$ as a limit when $\omega \to \infty$. Correspondingly I first increases, reaches a maximum when $dI/d\omega = 0$, or when:

$$\omega = \sqrt{\frac{R_1 R}{(K_{31} + A_2)(K_{24} + A_1)}} \tag{18}$$

and then decreases and reaches zero when $\omega = \infty$. Finally, the curve which represents the emf E_2 has a zero tangent at the point $\omega = 0$ and then increases continuously when ω increases. It has a point of inflection, and when $\omega \to \infty$, it approaches the limiting value given by:

$$(E_2)_{\omega=\infty} = \frac{K_{24}' + A_1'}{K_{31} + A_2} V_1 \tag{19}$$

or the value we would have, for each value of ω, if condition /378
(9) held true. Evidently, the smaller the value of the product R_1R as compared to the value of ω^2 $(K_{31}+ A_2)$ $(K_{24}+ A_1)$, the faster does the value of E_2 approach the limiting value (19).

The solution, as it has been considered, can be considered acceptable.

But it can be seen* that the one-loop amplidyne MT_2, compensated

* The observation explained here was made by engineer Giorgio Brach-Papa, who worked on the argument and discussed it in the thesis for his degree. The same engineer has also developed the calculations which have led to the determination of the theoretical characteristics plotted in Figure 9 and has carried out the modifications on the machine which was used to obtain the experimental measurements.

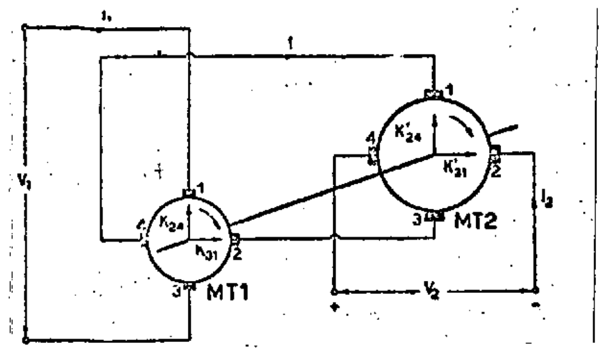

Figure 1. Initial theoretical diagram.

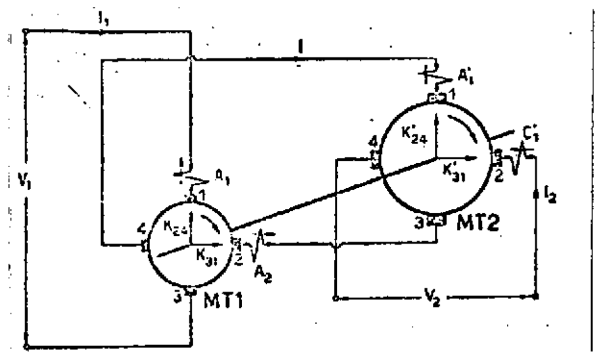

Figure 2. Diagram derived from the theoretical diagram shown in Figure 1, completed with windings which were theoretically shown to be advisable.

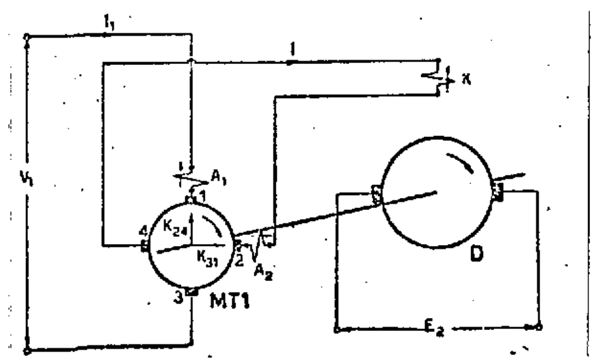

Figure 3. Diagram derived from the diagram shown in Figure 2 by replacing the main amplidyne with a simple generator with independent excitation.

completely on the secondary axis, with the primary circuit, which, not having any interference with the secondary circuit, only serves as the magnetizing circuit for the machine and does not need to be an amplidyne, but can be replaced without any particular inconvenience by a simple two-pole generator D as indicated on the diagram shown in Figure 3. The group then will consist of a simple generator D excited independently by means of the secondary current from the exciting amplidyne MT_1. Equations (14) and (15) still hold for this group since R always refers to the resistance of the circuit I_1 passes through, while the value of E_2 will be given by the equation:

$$E_2 = \omega K I \qquad (20)$$

where K is a constant which depends upon the design characteristics of generator D. For E_2 we now get the expression:

$$E_2 = \frac{\omega^2 K (K_{24} + A_1)}{\omega^2 (K_{21} + A_2)(K_{24} + A_1) + R_1 R} V_1 \tag{21}$$

which is completely analogous to (16) except that the term $K_{24}' + A_1'$ has been replaced by the term K.

An additional variation of the diagram shown in Figure 3 is the one indicated in Figure 4. It consists of the addition to the main generator excitation winding which the current I passes through and a second winding which current I_1 passes through. Its purpose is to increase the value of the total magnetizing ampere-turns for the lowest value of the speed since under these conditions current I_1 is largest as can be seen from (14). When this is done, Equation (20) should be replaced by:

$$E_2 = \omega (K I + K_1 I_1) \tag{22}$$

where K_1 represents the value of a constant, which is analogous to the constant K. Correspondingly, the value of the emf produced by the main generator is given by the expression:

$$E_2 = \frac{\omega [\omega K (K_{24} + A_1) + K_1 R]}{\omega^2 (K_{21} + A_2)(K_{24} + A_1) + R_1 R} V_1 \tag{23}$$

where the available parameters are more numerous than in expression (21), and it is thus possible, on the basis of calculations, to study the proportioning of the machines which are most suitable for achieving the goals previously established in the best way.

The observations made so far and the conclusions pertaining to them are based on the assumption that saturation phenomena do not take place in the magnetic circuits of the machine. It is evident that said phenomenon can not be disregarded and must be taken into account properly in the calculations. On the other hand, it is necessary to evaluate it in order to determine the dimensions of the machines in relation to their performance requirements.

Another element, which has not been mentioned in the theoretical considerations but is important from the point of view of the practical operation, is the addition of stabilizer windings to the amplidyne diagram. These windings are necessary to avoid electrical oscillations in the circuits.

The introduction of these windings modifies the results found above further. If in the case of the diagram shown in Figure 4 we assume that we add to the exciter amplidyne two stabilizer windings, a primary S_1 and a secondary S_2 as indicated in the diagram shown in Figure 5, the equations which represent the operation of the group become as follows:

$$\left\{\begin{aligned} &(R_1 + \omega S_1) I_1 + \omega (K_{31} + A_2) I && = V_1 \\ &\omega (K_{24} + A_1) I_1 - (R + \omega S_2) I && = 0 \\ &\omega K_1 I_1 + \omega K I && - E_2 = 0 \end{aligned}\right. \tag{24}$$

from which we derive the values:

$$I_1 = \frac{(R + \omega S_2)}{\omega^2 (K_{31}+A_2)(K_{24}+A_1) + (R_1 + \omega S_1)(R + \omega S_2)} V_1 \tag{25}$$

$$I = \frac{\omega (K_{24} + A_1)}{\omega^2 (K_{31}+A_2)(K_{24}+A_1) + (R_1 + \omega S_1)(R + \omega S_2)} V_1 \tag{26}$$

$$E_2 = \frac{\omega [\omega K (K_{24} + A_1) + K_1 (R + \omega S_2)]}{\omega^2 (K_{31}+A_2)(K_{24}+A_1) + (R_1 + \omega S_1)(R + \omega S_2)} V_1 . \tag{27}$$

Thus the introduction of the stabilizers causes the results to move further away from the desirable theoretical results.

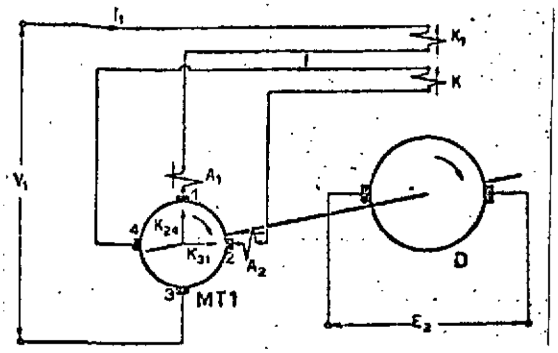

Figure 4. Modified diagram for Figure 3.

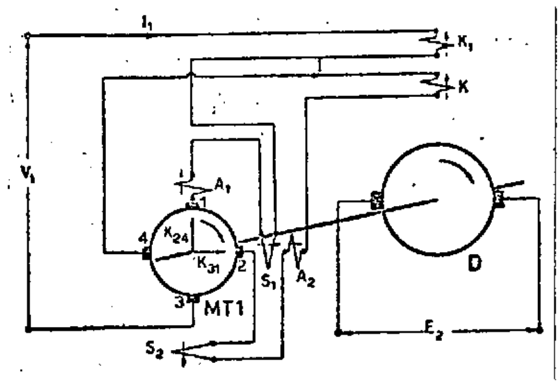

Figure 5. Practical diagram derived from the one for Figure 4.

3. - EXPERIMENTAL MEASUREMENTS

The theoretical considerations developed deserve to be verified experimentally, and this has been done by setting up a group according to the diagram shown in Figure 4. /379

For this purpose we use an amplidyne group with one control generator loop with four poles, appropriately modified.

The transformer amplidyne has been adapted to function as a generator by changing the connections of its armature windings properly, while the control generator, which has two pairs of poles and wave type armature windings, has been converted to a two-loop amplidyne giving it eight polar segments and appropriate characteristic windings. Four brushes are located in convenient positions on its collector.

The magnetic characteristics of the two machines have been obtained by measuring the voltage between pairs of brushes located 180 electrical degrees away from each other and by exciting the magnetic circuit with ampere-turns acting in a direction perpendicular to that of the theoretical axis of the brushes themselves. The ampere-turns have been measured by referring to one-half of a magnetic circuit as usual.

Figure 6 shows plots of two magnetic characteristics of the exciter generator obtained once by feeding the inductor coil and another time the armature between two brushes located 180 electrical degrees from each other. The two characteristics show that for the same number of ampere turns an mmf in the armature is more effective than an mmf in the inductor, and this is because of the utility of the flux dispersed in the interpolar space and around the front connections of the armature in the production of the useful flux.

Figure 7 shows the magnetic characteristic of the main generator obtained by exciting one winding of the inductor, since this method of excitation was the only one of interest for the experiments.

The magnetic characteristics have been used to derive the theoretical values for I_1, I and E_2 by means of Formulas (25), (26), and (27).

The calculations have been carried out by considering the values:

$$\begin{aligned} k_{31} = k_{24} &= 14.56 \text{ turns} \\ a_1 &= 100 \text{ turns} \\ a_2 &= 38 \text{ turns} \\ s_1 &= 6 \text{ turns} \\ s_2 &= 2 \text{ turns} \\ k_1 &= 62.5 \text{ turns} \\ k &= 82.5 \text{ turns} \end{aligned} \qquad (28)$$

where k_{31}, k_{24}, a_1, a_2, s_1, s_2, k_1, k indicate the number of turns, always for one-half of a magnetic circuit, of the windings which have been indicated by K_{31}, K_{24}, A_1, A_2, S_1, S_2, K_1, K and the values:

$$\left\} \begin{aligned} R_1 &= 2.34 \text{ ohm} \\ R &= 1.50 \text{ ohm} \end{aligned} \right. \qquad (29)$$

of the resistance in the circuit passed through by the currents I_1 and I, respectively.

For the calculation of the constants, reference has been made to the straight-line section of the magnetic characteristics since, from a practical point of view, the behavior of the group is more important when its speed of rotation is high, the currents are small and the magnetic circuits accordingly are not saturated. These straight-line sections are shown in the figures by means of straight lines tangent to the first section of each magnetic characteristic.

We then have:

a) for the exciter:

α) for excitation with inductor windings:
volt produced for $\omega = 1$ and for one ampere-turn of excitation

$$\frac{60}{2\pi 900} \cdot \frac{1}{2\,050}\, 100 = 0.00052;$$

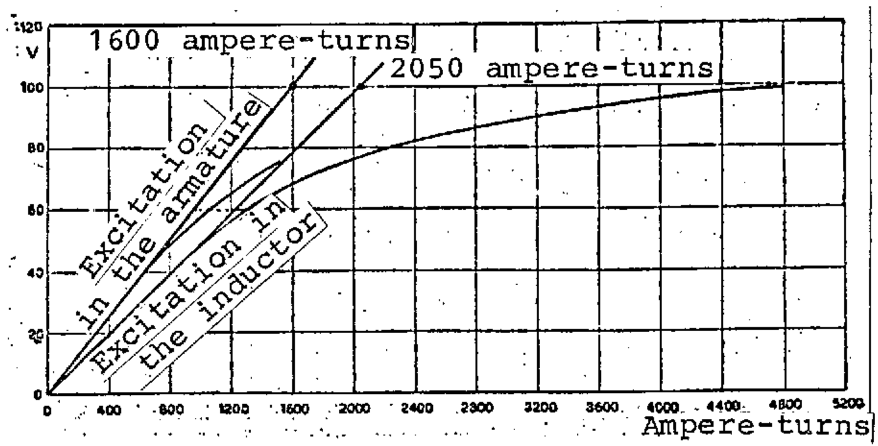

Figure 6. Magnetic characteristics of the exciting amplidyne.

β) For excitation with armature windings:
volt produced for $\omega = 1$ and for one ampere-turn of excitation

$$\frac{60}{2\pi\,900}\,\frac{1}{1\,600}\,100 = 0.00066;$$

b) for the main generator:

for excitation with inductor winding:
volt produced for $\omega = 1$ and for one ampere-turn of excitation

$$\frac{60}{2\pi\,1\,445}\,\frac{1}{1\,250}\,140 = 0.00074;$$

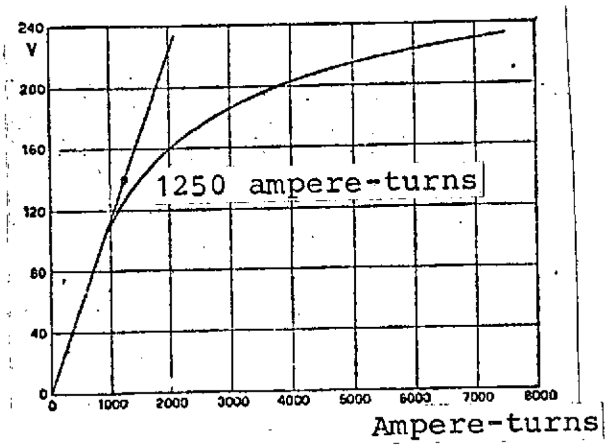

Fig. 7. Magnetic characteristics for the main generator.

And thus we derive for the exciter:

$$\left\{\begin{aligned} K_{31} = K_{24} &= 14.56 \cdot 0.00066 = 0.00961 \\ A_1 &= 100 \cdot 0.00052 = 0.05200 \\ A_2 &= 38 \cdot 0.00052 = 0.01976 \\ S_1 &= 6 \cdot 0.00052 = 0.00312 \\ S_2 &= 2 \cdot 0.00052 = 0.00104 \end{aligned}\right. \qquad (30)$$

and for the main generator:

$$\left\{\begin{aligned} K_1 &= 62.5 \cdot 0.00074 = 0.04625 \\ K &= 82.5 \cdot 0.00074 = 0.06105\,. \end{aligned}\right. \qquad (31)$$

We thus have all the elements necessary to be able to utilize Formulas (25), (26), and (27). /380

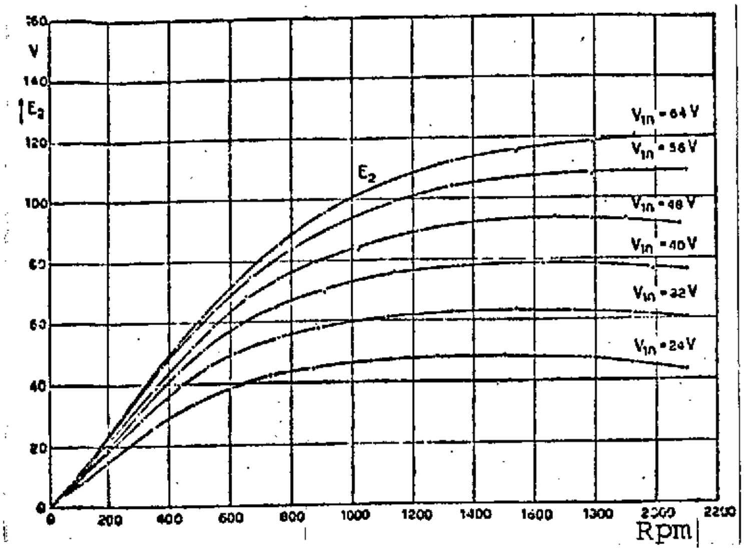

Figure 8. Characteristics which represent the measured values for E_2 as a function of the speed of the group for various values of the nominal voltage V_{1n}. The diagram in Figure 5 was used.

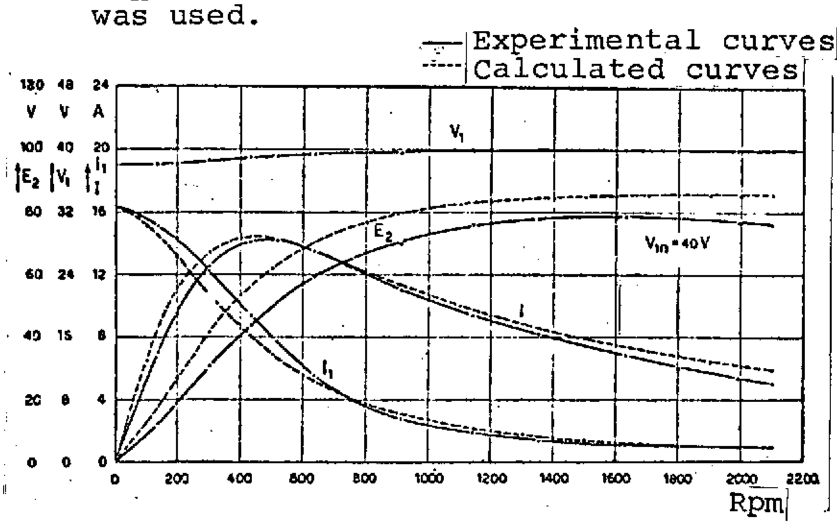

Figure 9. Characteristics which represent the measured values of V_1, the measured and calculated values for I_1, I, and E_2 as a function of the speed of the group and for nominal voltage V_{1n}=40 V. The diagram in Figure 5 was used.

The experimental measurements have been carried out by feeding the exciting amplidyne with the nominal values V_{1n} for the pilot voltage of 24; 32; 40; 48; 56; 64 volts, and for E_2 the curves plotted in Figure 8 were obtained.

Figure 9 shows plots of the measured characteristics (shown with solid lines) utilizing Formulas (25), (26), and (27), and the calculated characteristics (shown with dashed lines) for I_1, I, and E_2 for the nominal value V_{1n} for the pilot voltage of 40 volts. For each speed of the group, reference has been made in the calculations to the values of V_1 which were encountered during the experimental measurements.

An examination of the characteristics shows that the theoretical predictions were reasonable, and from a quantitative point of view it shows satisfactory agreement between the calculatid and the measured values. In particular,

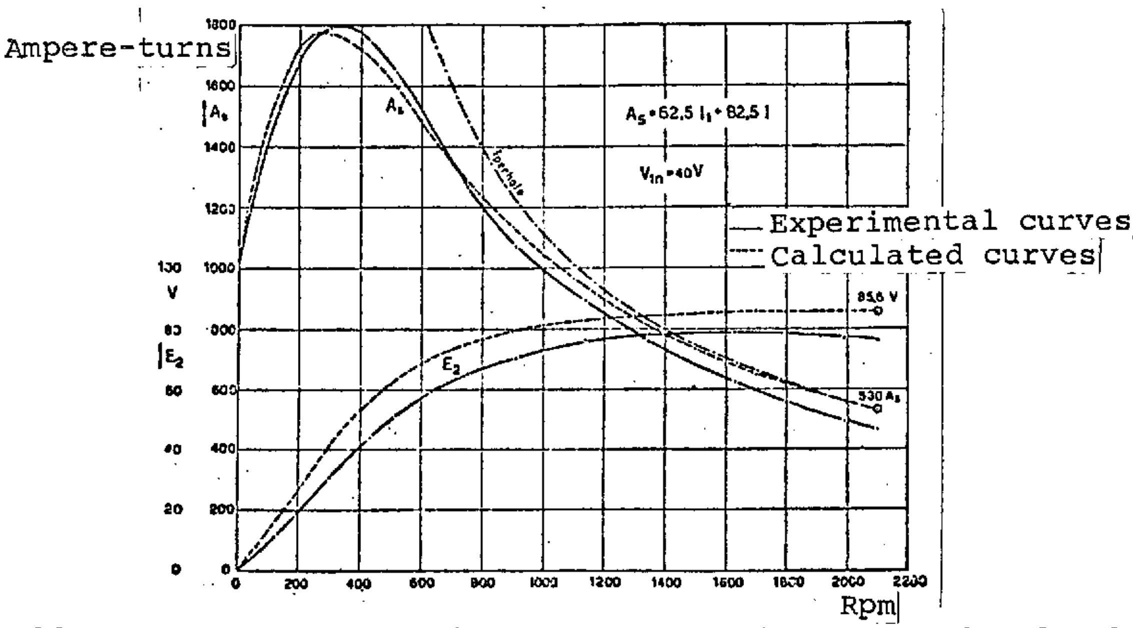

Figure 10. Characteristics which represent the measured and calculated values for E_2, the measured, calculated and theoretical (hyperbola) values for the total ampere-turns A_s of excitation in the main generator as a function of the speed of the group. The diagram in Figure 5 was used.

as far as the voltage E_2 is concerned, it is found that the measured value is always less than the calculated value, but its variation as a function of the velocity is similar to what was predicted by the calculations.

In Figure 10 are plotted, always as a function of the speed of the group expressed in rpm, the measured (shown with solid lines) and calculated curves (shown with dotted lines) of the voltage E_2 and the total number of ampere turns A_s of excitation for the main generator determined with the formula:

$$A_s = 62.5\, I_1 + 82.5\, I. \qquad (32)$$

For comparison, the curve the mmf A_s should have as a function of the velocity, if, disregarding saturation phenomena, the value V_2 were to remain constant for every speed and equal to the theoretical value of 85.6 volts, which it assumes for A_s = 530 ampere-turns at the speed of 21,000 rpm, has also been plotted on the same diagram.

The above curve is a hyperbola because, if we want the voltage produced by the main generator to remain constant and we disregard magnetic saturation phenomena, the product of the speed of rotation of the machine and the mmf A_s should remain constant.

4. - THEORETICAL STUDY OF A DIAGRAM COMPRISING ONLY A NORMAL DIRECT-CURRENT MACHINE

The last observation made concerning the plot of the curve of the mmf A_s provides the starting point for a consideration which leads to a solution for the problem under consideration by means of a diagram comprising only normal direct-current machines.

The main generator of the normal type already considered with two poles, excited independently, produces an emf E_2, which can be expressed by the formula:

$$E_2 = \frac{\omega}{2\pi} N \Phi . \tag{33}$$

where ω indicates the angular speed of rotation of its rotor in radians per second, N the number of conductors in the armature and ϕ the value of the induction flux per pole.

If we still disregard phenomena due to magnetic saturation /381 and we assume that the machine is excited with one single winding through which the current I flows, we can write:

$$\Phi = C I \tag{34}$$

were C is another constant. From this it follows that:

$$E_2 = \omega H I \tag{35}$$

where:

$$H = \frac{1}{2\pi} N C \qquad (36)$$

is one more constant.

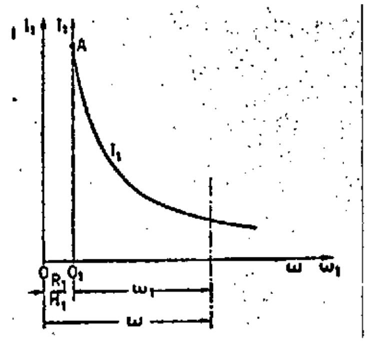

Fig. 11. A plot of the excitation curve I_1 produced by the direct-current generator of normal type with series excitation.

From (36) we deduce that the value of E_2 remains constant if:

$$\omega I = \text{constant} \qquad (37)$$

or if the current I varies as a function of ω, according to a curve represented by a hyperbola.

The current I, which meets the conditions now indicated, can be obtained with an exciter consisting of a direct-current machine with series excitation (the motor with series excitation of the normal type) fed by a pilot voltage V_1 of constant value.

In fact, by designating the total resistance of the circuit which the current I_1 passes through by R_1 and by designating a new constant by H_1 we can write:

$$V_1 = R_1 I_1 + \omega_1 H_1 I_1 \qquad (38)$$

where ω_1 refers to the angular velocity of the exciter rotor in radians per second. From (38) we obtain:

$$I_1 = \frac{V_1}{R_1 + \omega_1 H_1}. \qquad (39)$$

If we refer to the curve in Figure 11, we get:

$$\omega_1 = \omega - \frac{R_1}{H_1}, \tag{40}$$

we derive:

$$I_1 = \frac{V_1}{\omega H_1} \tag{41}$$

or:

$$I_1 \omega = \frac{V_1}{H_1} = \text{constant} \tag{42}$$

We thus conclude that the condition expressed by (42) will be satisfied if the speed of rotation of the generator with series excitation becomes equal to ω_1 and the speed of rotation of the main generator becomes equal to ω.

The condition now defined can be carried out by utilizing, as shown in Figure 12, a differential. The rotor of the series exciter machine E is connected to the housing of this differential by means of a geared speed multiplier, which doubles the speed. One of the shafts of the differential, which emerges from the housing, should be moved at the velocity ω by the main generator D, and the other should be moved in the opposite direction at a constant velocity R_1/H_1, for instance, by a direct-current motor M with shunt excitation and fed by the constant pilot voltage V_1.

With things arranged in this way, the main generator rotates with the speed ω the differential housing at the speed:

$$\frac{\omega_1}{2} = \frac{1}{2}\left(\omega - \frac{R_1}{H_1}\right), \tag{43}$$

while the exciter generator rotates with the speed ω_1 just like we wanted.

It is appropriate to note that the magnetic circuit of the exciter generator E saturates when the speed is low or when the main generator D needs higher excitation values or when the magnetic circuit itself saturates. But in these conditions, as can be easily confirmed by examining relationship (39), the decrease in the value of the constant H with respect to its value corresponding to the straight-line section of the magnetic characteristic of the exciter, makes sure that for the same ω the value of the current I_1 becomes larger and thus the effect of saturation on the main generator may become somewhat correct.

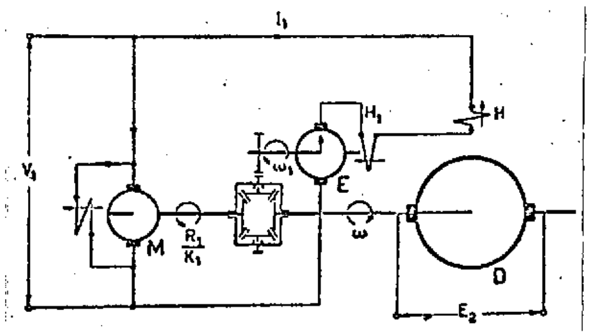

Figure 12. Diagram using only a normal direct-current machine.

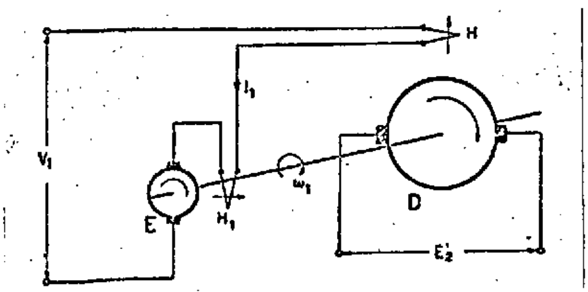

Figure 13. Diagram used in the experimental measurements pertaining to the diagram considered in Figure 12.

The particular theoretical curve for the current I_1 supplied by the exciter now considered and the observation we now made, lead us to assume that by using the diagram shown in Figure 11 it is possible to obtain a curve for the emf produced by the main generator which is practically constant over a very wide range of variation for the speed of the machine.

5. - EXPERIMENTAL DATA

Experimental data were obtained by using the last /382 diagram considered with the same machines which were used for the data which have already been illustrated.

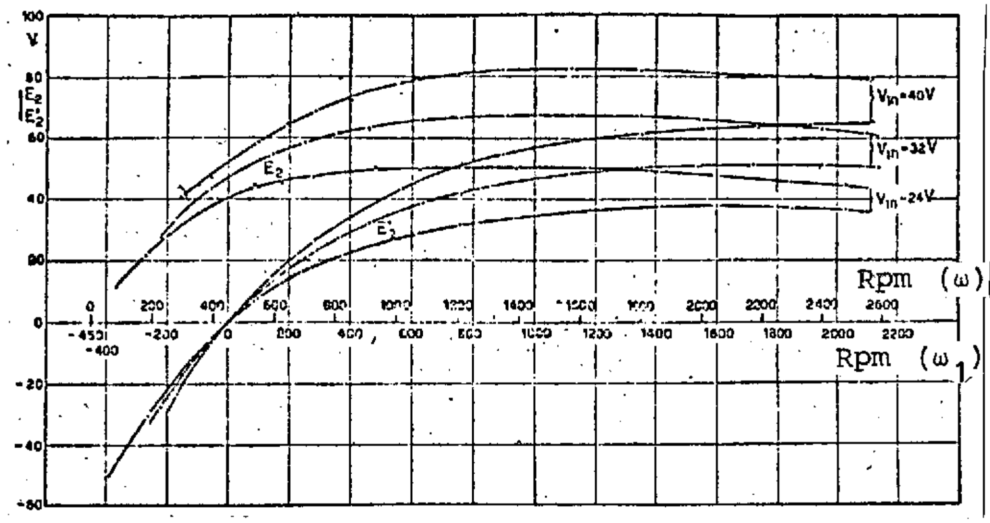

Fig. 14. Characteristics which represent the calculated values for E_2 as a function of the speed of the group derived from the characteristics plotted for E_2' for various values of the nominal voltage V_{1n}. The diagram in Figure 13 was used.

Since we did not have a differential available, we decided to make the exciter and the main generator rotate at the same speed, because since the purpose of the research was to measure the no-load emf produced by the main generator, its speed of rotation, although it was known, could assume any value.

The diagram used was the one illustrated in Figure 13. The measurements were made while feeding the four-pole exciter generator E with the pilot voltage of nominal values:

$$V_{1n} = 24 \ ; \ 32 \ ; \ 40 \ V. \tag{44}$$

The values of V_1, I_1, and E_2' were measured as a function of the speed using the 38 turns per pole winding to excite the exciter (winding H_1) and the 62.5 turns per pole winding to excite the main generator (winding H).

The values of E_2 have been calculated from the values for E_2' referring to the speed ω the main generator should have had instead of the speed the group was made to operate at or to the speed ω increased by the quantity R_1/H_1, which was considered in expression (40). In the particular case pertaining to the experiment we have:

$$\left\{\begin{array}{l} R_1 = 0.935 \\ H_1 = 0.01976 \end{array}\right| \text{(from winding } A_2\text{)} \tag{45}$$

and thus we get:

$$\frac{R_1}{H_1} = \frac{0.935}{0.01976} = 47.2 \text{ rad/sec} \tag{46}$$

which corresponds to:

$$47.2 \frac{60}{2\pi} = 450 \text{ giri/min.} \tag{47}$$

The curves of the values of E_2' and E_2, the latter derived from E_2', are shown as functions of the speed in Figure 14.

Figure 15 shows the characteristics which represent the measured values of V_1, I_1 as a function of the speed of the group in rpm. The vertical axis is also shown passing through the abscissa at -450 rpm which constitutes, like the axis of the abscissa, an asymptote of the theoretical hyperbolas also shown in the figure. The theoretical hyperbolas correspond to theoretical values for the current I_1 as a function of the speed when H_1 is considered to be equal to 0.01976 and it is assumed that there are no saturation phenomena in the magnetic circuit. The hyperbolas can be constructed immediately if we realize that they should always pass through the point A, indicated in Figure 11, for which the speed of the exciter is equal to 0 and we have the following simple relationship:

$$I_1 = \frac{V_1}{R_1}. \tag{48}$$

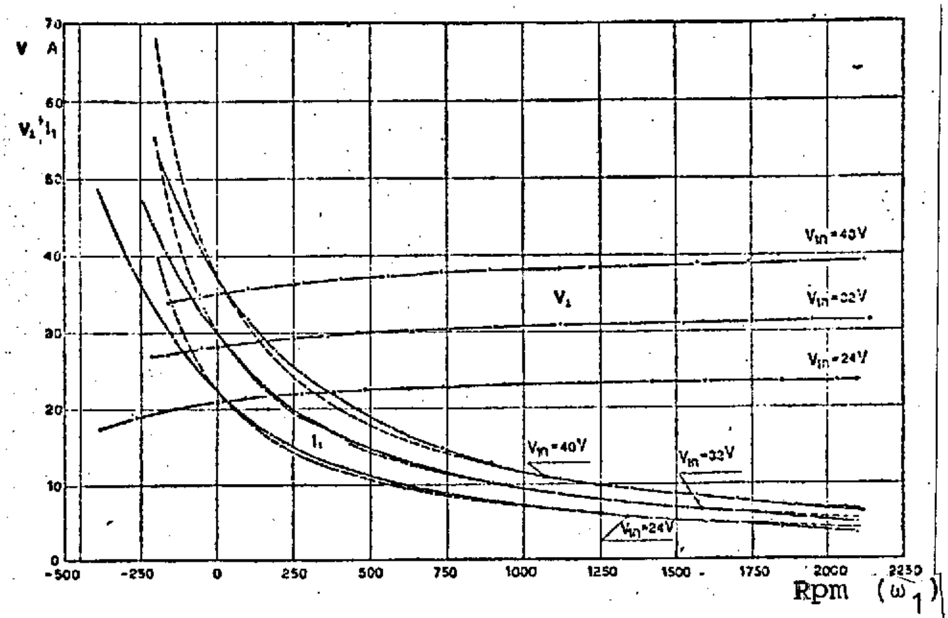

Figure 15. Characteristics which represent the values measured for V_1 and I_1 as a function of the speed of the group for the nominal voltages V_{1n} = 24, 32 and 40 volts, and corresponding theoretical curves, shown with dotted lines, of the characteristics (hyperbolas) which represent the current I_1 if there is no saturation in the magnetic circuits of the exciter generator. The diagram is that of Figure 13.

6. - FINAL OBSERVATIONS

In the description made it was shown that it is possible to build groups of direct-current generators which, when driven by wind engines, are capable of producing electrical energy at practically constant voltage when the speed of the first engine varies within very wide limits. In order to use the energy produced, it can be fed into a network of normal voltage. In order to do this, it is necessary that the characteristics of the energy itself be conveniently regulated. First of all, it is necessary to regulate the voltage produced by the generator. This can be done by regulating the pilot voltage V_1. The regulator should be sensitive to the speed of the electrical generator, and at each speed it should change the voltage in the correct direction until the generator delivers the power which, except for the losses, can be supplied to it by the first motor. The generator should be proportioned in such a way that it will be able to carry the maximum current load which exists at the highest speed and the maximum flux which exists at the lowest speeds. Economic considerations pertaining to the construction of the plant, which depend upon the limits within which the wind energy may conveniently be utilized for the various wind speeds, should be made to establish the maximum predicted loads or the limits for the power of the wind engine. /383

Concerning the two diagrams considered, the second, which consists only of machines of the normal type, seems to be better because in this diagram the electric generator can produce a voltage which is practically constant between wider limits than for the other diagram. It should still be noted that with this diagram it is possible to regulate the emf E_2 by means of a variation in the shunting of the series excitation winding of the exciter generator. Although its machines are simple in construction, for otherwise equal conditions, the excitation current, being unique, must reach higher values than when the excitation is by an amplidyne, and thus the thermal stress in the armature of the exciter will be greater.

In both diagrams the power consumed in the exciter is not being lost since it is passed on to the shaft of the main generator, except for losses.

Finally, it seems that it would be convenient if the machines had a relatively wide air gap so that their magnetic characteristics would be as linear as possible for the lowest induction values, since when the group is rotating at high speeds, the current values are small and the irregularities in the magnetic characteristics with respect to the straight-line curve and thus the irregularities in the generation of the emf are more prominent percentage wise.

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